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13. ABSTRACT (Maximum 200 words)

The study of a new class of mesoscopic high frequency semiconductor devices based on resonant tunneling in staggered-bandgap heterostructures with III-V semiconductor ternary alloys such as AlGaSb and InAsSb has been made. In staggered-bandgap heterostructures even electron energy levels and their wave functions cannot be determined in the framework of one band model . The multiband model calculation predicts four quasi-discreet levels in the quantum well of AlGaSb/InAs/AlGaSb double barrier structures while only two electron levels have been obtained in one band model. A multiband model of the semiconductor materials has been developed .The model includes six bands: two conduction bands, two light- and two heavy-hole valence bands. The multiband equations have been used to calculate the quasi-discrete energy levels and wave functions for electrons in the quantum well of the Resonant Tunneling Diodes with AlGaSb/InAs/AlGaSb double barrier structures . The current-voltage characteristics has been calculated in the frame of the sequential tunneling model. The current-voltage characteristics are very sensitive to the width of the spacer. An electron transport within the conduction band is highly dependent on the coupling between the conduction and valence bands and an accurate estimate of current density requires the application of a multi-band model. A six-band Kane model yields very good agreement with experimental measurement.

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MULTI-BAND MODEL OF RESONANT TUNNELING DIODES WITH STAGGERED-BANDGAP HETEROSTRUCTURES

In recent years, resonant tunneling diodes (RTDs) gained considerable attention as potential low-power sources of electromagnetic energy in submillimeter-wave region. Specifically, the extremely fast response associated with the negative differential resistance (NDR) of RTDs was seen as a viable gain mechanism for the generation of terahertz (THz) energy. Unfortunately, while double-barrier RTD's have been implemented as two-terminal oscillators up to 712 GHz [1] the power output levels have been restricted to microwatt levels primarily as a result of low-frequency design constraints (i.e., suppression of bias circuit oscillations). In fact, these fundamental limitations in the conventional implementation of RTDs as oscillation sources have motivated new study of "intrinsic" instabililty mechanisms [2]. This research addresses a novel mesoscopic charge-feedback effect in staggered-bandgap structures as a potential new solution.

Specifically, staggered bandgap heterostructures can admit significant interband tunneling currents. Hence, the possibility exists that these interband currents might be engineered to develop a nanoscale feedback between adjacent valence and conduction band wells. This novel use of nanotechnology seems extremely feasible from a fundamental perspective; however, detailed theoretical studies will be required to enable a useful insight into the basic phenomenon. The goal of this research has been to establish an accurate description of the electron transport within resonant tunneling diodes with staggered-bandgap heterostructures.

The device is based on a type II resonant tunneling structure, i.e. a structure in which the quantum well and barrier semiconductors possess a type II band gap alignment to each other (Fig. 1). Here, the quantum well is formed by InAs sandwiched between two barrier regions (AlGaSb/InAs/AlGaSb double barrier structures). The left $Al_xGa_{1-x}Sb$ (x=0.4) barriers is adjacent to a highly doped InAs emitter while the right barrier is adjacent to the undoped InAs spacer which is grown on the highly doped InAs collector region. Note that the right barrier can also function as a quantum well for holes. As has been shown, this structure allows electrons to reside in the quantum-well layer and allows for hole trapping in the right quantum-barrier layer.

Under moderate levels of applied bias voltage, the staggered-bandgap allow for an alignment of quantum-barrier states with the empty states in the undoped collector spacer. Hence, significant interband tunneling currents result and leads to a buildup of holes in the valence band well via the staggered-bandgap channel. An electron-hole dipole is then formed and that may be subsequently discharged by properly specifying the charging process of the conduction-band well. An intrinsic bistability is observed in resonant tunneling diodes utilizing these structures due to the two different steady-state charge distribution that result for a single bias voltage [3].

The "qualitative" explanation of the observed bistability has been given by Buot and Rajagopal [4]. They underlined the importance of the Zener tunneling and trapped holes in these structures and have shown that a hysteresis can be realized in AlGaSb/InAs/AlGaSb double barrier structures.

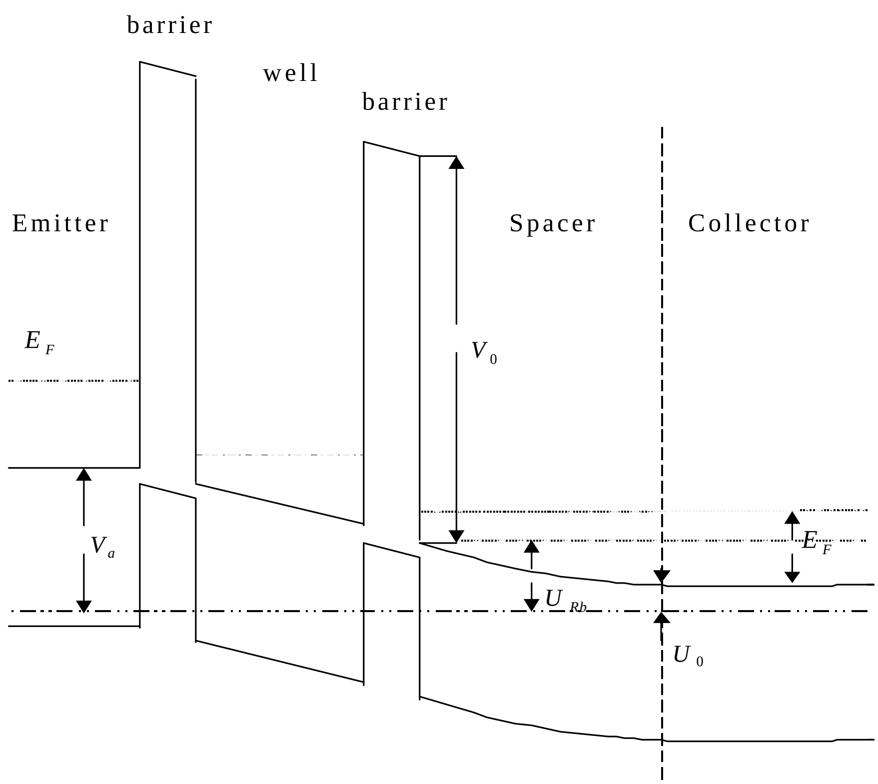

Figure 1. The band diagram of device structure

We have developed a “quantitative” model for staggered-bandgap heterostructures This model includes: 1) interband Zener tunneling of valence-band electrons into the collector conduction and 2) hole resonant tunneling from the barrier through the well into emitter. A multiband description of electron and hole energy levels is incorporated into the quantitative model for an accurate study of interband resonant tunneling diodes.

Our first goal was to find the existence of multiple stationary states in the I-V characteristic of the interband resonant tunneling diode (IRTD). The preliminary analysis was made by neglecting the temperature dependence of the distribution functions for electrons and holes in the well and the barrier, respectively.

In this analysis of the current-voltage (I-V) characteristic a sequential tunneling model [5] has been utilized. As shown, the hole-charge strongly influences the spatial distribution of the potential and as result modifies the overall electron current. At threshold voltage, where the position of the quantum-well resonant level becomes lower than the bottom of the conduction band in the emitter, a drastic drop in the electron current occurs. This is a familiar result as no electrons are available for the well-state resonant level. At higher voltages, a state with zero electron current can be realized due exclusively to interband hole tunneling . This second state persists below the threshold voltage and creates a hysteresis in the I-V results. The extent of this duality in the I-V characteristics of the IRTD strongly depends on the spacer length and verifies the important influence of the interband tunneling mechanism. The current-voltage characteristics have been calculated. It proved that the current-voltage characteristics are very sensitive to the width of the spacer. In particular the interband Zener tunneling of valence-band electrons of the right barrier into the collector conduction band becomes possible only if the spacer width is sufficiently large .

However, the sequential tunneling model can be used self-consistently for the single band conduction band model at the moderate field. When determining the out-coming flux in the sequential tunneling model only decaying solution of the Schrodinger equation is taken into account. The analogous model can be developed in the case of non-constant potential in the barrier if we consider quasi-classical limit of the solution of the Schrodinger equation . However, the Zener tunneling has to be considered in strong fields. Hence, as the first proper approach we have considered the conventional quantum mechanical problem of multiband tunneling in RTDs.

We have investigated RTDs based on a type II resonant tunneling structure, i.e. a structure in which the quantum well and barrier semiconductors possess a type II band gap alignment to each other. The quantum well is formed by InAs sandwiched between two barrier regions (AlGaSb/InAs/AlGaSb double barrier structures). We have shown that for staggered-bandgap heterostructures even electron energy levels and their wave functions cannot be determined in the framework of one band model . For example we obtain two electron levels for AlGaSb/InAs/AlGaSb double barrier structures according to one band model. The multiband model calculation predicts four quasi-discrete levels in the quantum well. The position of levels is crucial for the current-voltage characteristics of the RTDs . We have developed a multiband model of the semiconductor materials which includes all relevant valence and conduction bands for the proper description of their interaction. The model includes six bands: two conduction bands, two light- and two heavy-hole valence bands.

At lower bias voltages the current within RTDs with staggered-bandgap structures (SBSs) is dominated by conduction-band electron transport. Hence, the first step towards an accurate description of these devices is the development of an adequate physical model for the electronic motion in the conduction band. In most investigations of conduction-band tunneling processes the analysis considers single-band transport and ignores any coupling (e.g., arising out of changes in effective mass at the hetero-interfaces) between the transverse (i.e., perpendicular to the barriers) and in-plane wave-vector components. However, in SBSs it is not sufficient to apply such decoupled methods even if one is only interested in the conduction-band electrons (i.e., electrons with energies lying in the conduction band). It is very important to recall that the luxury of utilizing single-band transport models is made possible only because energy within the band of interest is relatively low. Specifically, because the in-band energy is relatively small compared to the energy gaps between the band of interest and all

lower energy bands. Since the SBS under consideration contains InAs and AlGaSb layers, with relatively narrow bandgaps, one must apply the six-band Kane model with properly coupled multi-band wave functions.

The multiband equations have been used to calculate the energy levels and wave functions for electrons in the quantum well in the RTDs with AlGaSb/InAs/AlGaSb double barrier structures . As has been shown, electron transport within the conduction band is highly dependent on the coupling between the conduction and valence bands and an accurate estimate of current density requires the application of a multi-band model. A six-band Kane model yields very good agreement with experimental measurement (Fig.2).

This research represents an early, and necessary step towards a fully time-dependent analysis of the transport physics and a complete understanding of nanoscale feedback within staggered-bandgap heterostructures.

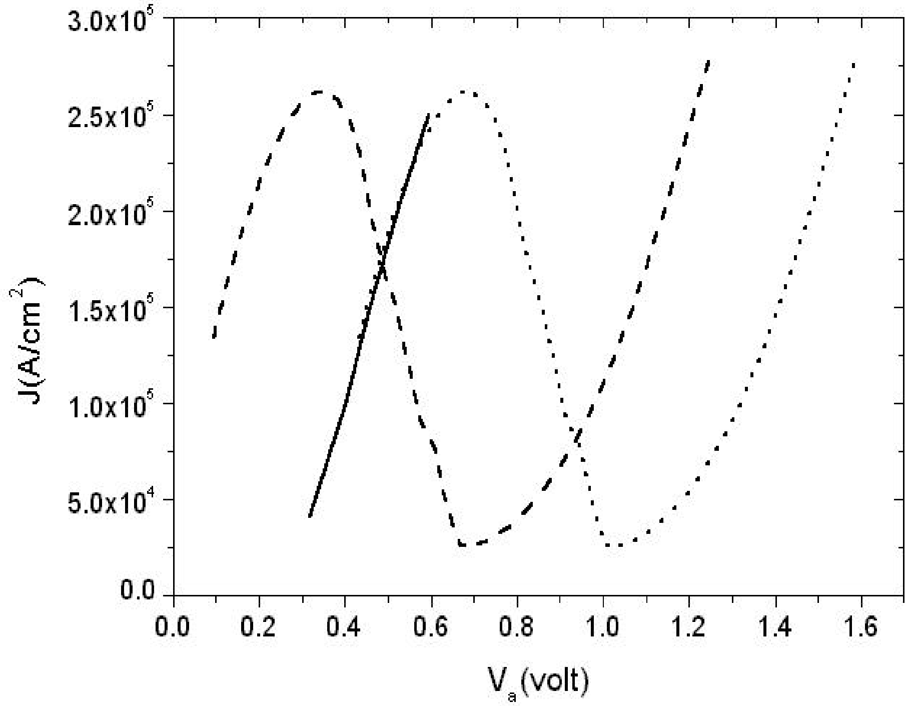

Figure 2. The solid line represents experimental data (ref.[3]) ,the dash line is based on theoretically calculated results and the dot line is shifted 0.34 V from the dashed one. Component x=0.5, the doping is $2.2x10^{18}/cm^3$.

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